InLCA: Case Studies – Using LCA to Compare Alternatives

Comparative LCAs for Curbside Recycling Versus Either Landfilling or Incineration with Energy Recovery

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Abstract

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Background. This article describes two projects conducted recently by Sound Resource Management (SRMG) – one for the San Luis Obispo County Integrated Waste Management Authority (SLO IWMA) and the other for the Washington State Department of Ecology (WA Ecology). For both projects we used life cycle assessment (LCA) techniques to evaluate the environmental burdens associated with collection and management of municipal solid waste. Both projects compared environmental burdens from curbside collection for recycling, processing, and market shipment of recyclable materials picked up from households and/or businesses against environmental burdens from curbside collection and disposal of mixed solid waste.

Methodology. The SLO IWMA project compared curbside recycling for households and businesses against curbside collection of mixed refuse for deposition in a landfill where landfill gas is collected and used for energy generation. The WA Ecology project compared residential curbside recycling in three regions of Washington State against the collection and deposition of those same materials in landfills where landfill gas is collected and flared. In the fourth Washington region (the urban east encompassing Spokane) the WA Ecology project compared curbside recycling against collection and deposition in a waste-to-energy (WTE) combustion facility used to generate electricity for sale on the regional energy grid. During the time period covered by the SLO study, households and businesses used either one or two containers, depending on the collection company, to separate and set out materials for recycling in San Luis Obispo County. During the time of the WA study households used either two or three containers for the residential curbside recycling programs surveyed for that study. Typically participants in collection programs requiring separation of materials into more than one container used one of the containers to separate at least glass bottles and jars from other recyclable materials. For the WA Ecology project SRMG used life cycle inventory (LCI) techniques to estimate atmospheric emissions of ten pollutants, waterborne emissions of seventeen pollutants, and emissions of industrial solid waste, as well as total energy consumption, associated with curbside recycling and disposal methods for managing municipal solid waste. Emissions estimates came from the Decision Support Tool (DST) developed for assessing the cost and environmental burdens of integrated solid waste management strategies by North Carolina State University (NCSU) in conjunction with Research Triangle Institute (RTI) and the US Environmental Protection Agency (US EPA)[1]. RTI used the DST to estimate environmental emissions during the life cycle of products. RTI provided those estimates to SRMG for analysis in the WA Ecology project[2]. For the SLO IWMA project SRMG also used LCI techniques and data from the Municipal Solid Waste Life-Cycle Database (Database), prepared by RTI with the support of US EPA during DST model development, to estimate environmental emissions from solid waste management practices[3]. Once we developed the LCI data for each project, SRMG then prepared a life cycle environmental impacts assessment of the environmental burdens associated with these emissions using the Environmental Problems approach discussed in the methodology section of this article. Finally, for the WA study we also developed estimates of the economic costs of certain environmental impacts in order to assess whether recycling was cost effective from a societal point of view.

Conclusions. Recycling of newspaper, cardboard, mixed paper, glass bottles and jars, aluminum cans, tin-plated steel cans, plastic bottles, and other conventionally recoverable materials found in household and business municipal solid wastes consumes less energy and imposes lower environmental burdens than disposal of solid waste materials via landfilling or incineration, even after accounting for energy that may be recovered from waste materials at either type disposal facility. This result holds for a variety of environmental impacts, including global warming, acidification, eutrophication, disability adjusted life year (DALY) losses from emission of criteria air pollutants, human toxicity and ecological toxicity. The basic reason for this conclusion is that energy conservation and pollution prevention engendered by using recycled rather than virgin materials as feedstocks for manufacturing new products tends to be an order of magnitude greater than the additional energy and environmental burdens imposed by curbside collection trucks, recycled material processing facilities, and transportation of processed recyclables to end-use markets. Furthermore, the energy grid offsets and associated reductions in environmental burdens yielded by generation of energy from landfill gas or from waste combustion are substantially smaller then the upstream energy and pollution offsets attained by manufacturing products with processed recyclables, even after accounting for energy usage and pollutant emissions during collection, processing and transportation to end-use markets for recycled materials. The analysis that leads to this conclusion included a direct comparison of the collection for recycling versus collection for disposal of the same quantity and composition of materials handled through existing curbside recycling programs in Washington State. This comparison provides a better approximation to marginal energy usage and environmental burdens of recycling versus disposal for recyclable materials in solid waste than does a comparison of the energy and environmental impacts of recycling versus management methods for handling typical mixed refuse, where that refuse includes organics and non-recyclables in addition to whatever recyclable materials may remain in the garbage. Finally, the analysis also suggests that, under reasonable assumptions regarding the economic cost of impacts from pollutant emissions, the societal benefits of recycling outweigh its costs.

Keywords: Combustion; emissions valuation; energy conservation; incineration; landfill; LCA; LCI; lifecycle; pollutant valuation; pollution prevention; recycling; resource conservation; waste-to-energy

[1] (RTI 1999a), (RTI 1999b), (Barlaz 2003a), and (Barlaz 2003b).

[2] See Appendix A, Single-Family Residential Curbside Recycling Case Study in (WA Ecology 2002) for a detailed description of the data, methods and analyses used in the WA Ecology project.

[3] Both the DST and its Database are intended to be eventually available for sale to the public by RTI. Contact Keith Weitz at kaw@rti.org for further information on public release dates for the DST and the Database.

1 Brief History of Development of the DST and its Associated Database

Industry and governmental agencies have been tracking emissions of certain pollutants to the air and water for a number of years. During the past fifteen years researchers have begun to use these data along with other information to prepare life-cycle inventory (LCI) studies on solid waste management systems that handle the materials generated as residuals from production and consumption activities. These LCI studies have examined the life cycle of products, beginning with the acquisition from natural ecosystems of raw materials and fuels used for manufacturing a product, all the way through to management of residuals at the end of the product's life, so as to determine material and energy inputs and waste outputs and environmental releases associated with production, use and end-of-life management of that product.

Over much of the past decade RTI has been managing a project, with extensive financial and in-kind support from US EPA and with assistance from NCSU, to develop the DST to model municipal solid waste management systems in an optimizing framework. A significant goal of the project was to create a model and database that could assist local communities, as well as others involved in handling solid wastes and managing facilities, in their quest to find waste management systems that achieve and/or balance the twin goals of being cost-effective and minimizing environmental impacts. The structural equations and emissions data that are contained in the DST and its Database have been informed by an extensive peer and multi-stakeholder review process conducted by US EPA and RTI.

As with any intellectual inquiry there remain several serious substantive debates regarding assumptions and default parameters in the DST, e.g., the modeling of landfill liner failure and the capture efficiency for landfill gas collection systems. In addition, the number of pollutant emissions modeled for the life cycle of consumer products and for solid waste management facilities and processes that handle products at the end of their useful lives is quite small in comparison to the actual number of chemical substances used and emitted during resource extraction and refining, product manufacturing and product end-of-life management. Despite these shortcomings, the DST and its associated Database provide very thoroughly reviewed and relatively comprehensive tools for quantification of environmental burdens entailed in using a wide variety of methods for managing municipal solid wastes.

2 Methodology for SLO IWMA and WA Ecology Studies

The methodology used in the two studies described in this article involved five distinct steps:

(1) Data Collection: For the WA study SRMG surveyed numerous residential curbside recycling programs in each of four natural divisions of the state – urban areas west of the Cascade Mountain chain, rural areas west of the Cascades, urban areas east of the Cascades and rural areas east of the Cascades. We defined these four regions according to demographic and geographic characteristics of solid waste collection service customers. Survey data included quantities of recyclable materials collected, collection route characteristics such as average time and distance between stops and number of households serviced on a route, distances from recycling or refuse collection route end points to processing or transfer facilities, and distance from transfer facilities to disposal facilities. In the SLO County study the IWMA provided information to SRMG on quantities of recyclables and refuse collected curbside in the large contiguous southern portion of the county serviced by the Cold Canyon collection companies, as well as data on the quantities of each type of processed material sold to recycling end-use markets and the separate quantities of diesel consumed for curbside/on-site recycling and curbside/on-site refuse collections from households and businesses.

(2) Preparation of Data for Analysis: In the WA study SRMG calculated sample averages from the survey data so as to characterize the average residential curbside recycling program for each of the four regions. RTI augmented these averages with DST defaults for distance to recycling markets because actual data on those distances proved unavailable in the survey. For the SLO study SRMG augmented IWMA information on collection quantities, processing quantities, landfill quantities and diesel usage for collection with estimates of the energy usage and environmental burdens from production of collection vehicles. These estimates came from Carnegie-Mellon's Green design Initiative Economic Input-Output Life Cycle Assessment (EIO-LCA) model[4].

(3) Life Cycle Inventory (LCI) Calculations: For the WA study RTI used the DST to calculate life cycle energy usage and pollutant emissions associated with curbside collection, processing and marketing of recyclables, and to calculate energy and pollutant emissions associated with refuse collection and disposal of the same quantity and composition of materials as handled in the curbside recycling systems. In the SLO IWMA study SRMG used the DST Database to calculate energy usage and pollutant emissions associated with curbside/on-site collection of recyclables and curbside/on-site collection of refuse. Furthermore, at the time of these two studies RTI had not fully incorporated into the DST and Database complete estimates of the global warming benefits from carbon sequestration in forests due to recycling of paper. To compensate for this lack SRMG used US EPA's WARM model to include carbon sequestration in forests in the calculation of upstream energy conservation and pollution prevention benefits from paper recycling in both studies[5].

(4) Life Cycle Environmental Impacts Assessment: For both studies SRMG used the Environmental Problems approach to impact assessment as developed in the early 1990s within the Society for Environmental Toxicology and Chemistry (SETAC). This approach is codified in the National Institute of Standards and Technology's Building for Environ-

[4] This model is available on the Internet at www.eiolca.net. The EIO-LCA model attaches a matrix of energy usage and pollutant emissions for each industry to an input-output model of the US economy in order to compute a life cycle inventory for products produced by each industry.

[5] WARM is available on the Internet at www.epa.gov/globalwarming/actions/waste/warm.htm. See (USEPA 2002a) for the methodology and research that supports this model.

mental and Economic Sustainability (BEES) 3.0 model (Lippiatt 2002), and supported by US EPA Office of Research and Development's recent development of TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts)[6]. SRMG assessed six environmental impacts using the BEES codifications – global warming potential, acidification potential, eutrophication potential, human health impacts potential from releases of criteria air pollutants, human health impacts potential from toxic releases, and ecological impacts potential from toxic releases.

(5) Economic Evaluation of Environmental Impacts: SRMG carried out the last step of a complete LCA – the economic valuation of impact costs – only for the WA Ecology study. SRMG used the midpoint of cost estimates from four studies and average prices from recent market trades for pollutant emissions permits/agreements, and weighted those midpoint estimates by BEES weights for pollutants in each impact category in order to calculate an economic cost for three environmental impacts – global warming, acidification and eutrophication[7,8].

3 Discussion of Results for the SLO IWMA Study

During 2002 the Cold Canyon companies collected 22,009 metric tons or megagrams (Mg, i.e., a million grams or a thousand kilograms) of recyclables and 95,188 Mg of refuse in their service areas. These collection areas comprise the southern part of San Luis Obispo County and include most of the households and businesses in that county. The composition of collected recyclables was approximately 40.4% mixed and office paper, 20.6% glass, 16.5% cardboard, 15.7% newspapers, 4.1% plastic, 2.1% steel and 0.6% aluminum. Due to a lack of composition data for SLO County refuse, SRMG used the DST's default national average waste composition profile to characterize collected refuse.

3.1 Energy savings from recycling compared with landfilling

Fig. 1 shows estimated energy used in 2002 for collecting recyclables and refuse, and delivering those respective quantities to processing and landfill facilities. Fig. 1 also shows estimated energy used in 2002 for operating the landfill, processing and shipping recyclables to end-use markets, and manufacturing processed recyclables into new products. Energy usages for these components of SLO County's recycling and disposal systems are shown as positive portions of the respective stacked bars for Recycling Impacts and Garbage Impacts in Fig. 1.

The energy conserved from recycling, as a result of avoiding the manufacture of new products from virgin raw materials, is shown as the negative portion of the stacked bar for Recycling Impacts. Producing products such as newsprint, cardboard, glass containers, aluminum can sheet and plastic pellets with virgin materials requires 25.7 million Btus, compared with the 11.4 million Btus needed to make this same quantity and mix of products with the recycled material components that were, on average, in each metric ton of materials collected for recycling from SLO County households and businesses during 2002.

[6] TRACI is a set of state-of-the-art, peer-reviewed US life cycle impact assessment methods. See (US EPA 2002b) and (Bare 2002). The BEES weights for assembling pollutant emissions into impact categories are given in the BEES 3.0 manual (Lippiatt 2002).

[7] Cost estimates for the four studies and average prices for market trades are listed in Table 4, Economic Valuation of Atmospheric and Waterborne Emissions in (Ecology 2002).

[8] In currently ongoing studies SRMG also has calculated the economic value of avoided environmental impacts on human and ecological health.

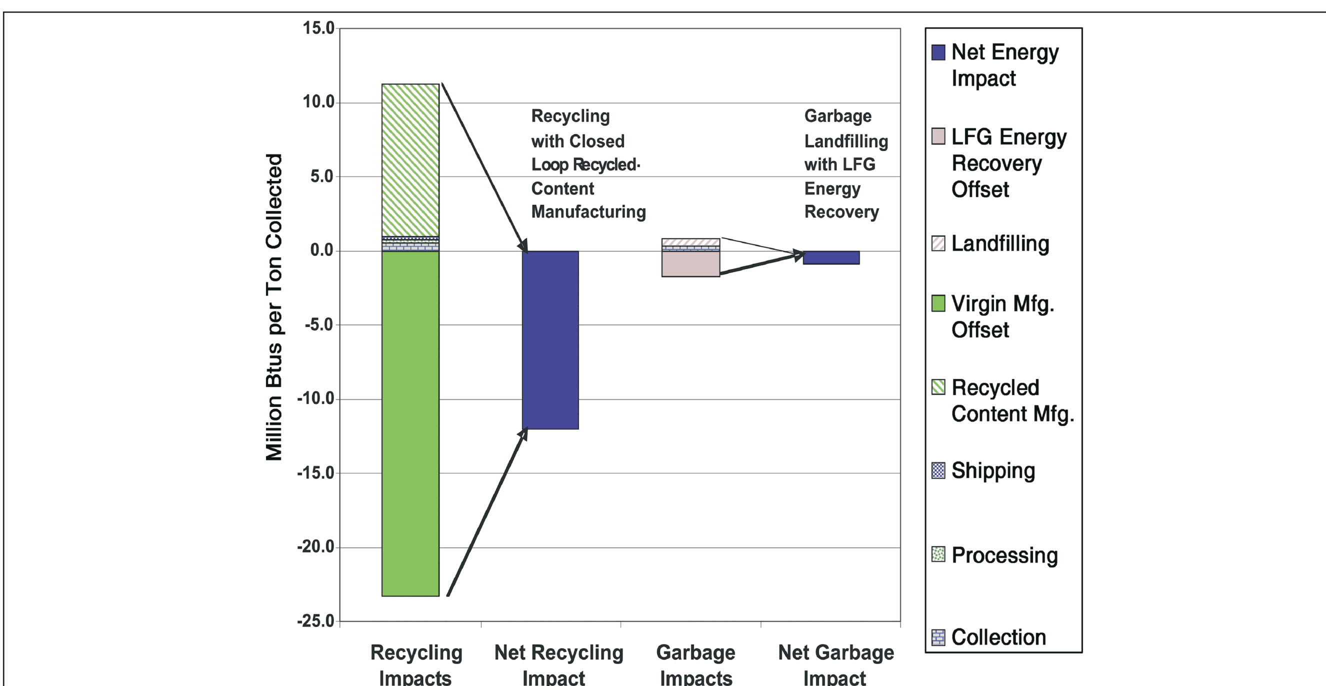

Fig. 1: Comparative energy usage for SLO recycling vs. landfilling

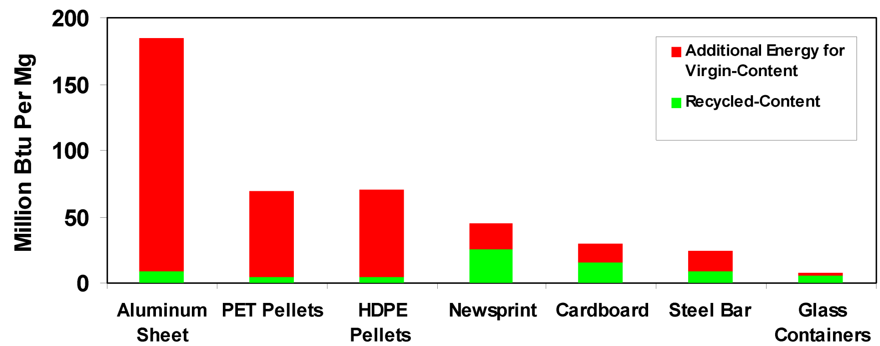

Fig. 2: Comparative energy usage for recycled- vs. virgin-content products

Fig. 2 shows these energy savings for the closed-loop, recycled-content manufactured products that can use SLO's recycled materials as feedstocks. As indicated in Fig. 2, recycled-content products require much less energy than virgin-content products. Recycled-content aluminum sheet and plastic pellets require between 5% and 7% of the energy needed to make these items from virgin raw materials. Recycled-content steel requires about 37% of the energy required for virgin steel. Recycled-content newsprint and cardboard use less than half the energy required for virgin. Even recycled-content glass containers only require 65% of the energy needed to produce virgin-content glass jars.

Given the mix of paper, plastic, metal and glass materials recycled in SLO County, these estimated energy savings for individual recycled-content products yield the estimate that producing products with SLO's recycled materials uses only 44% as much energy as would be required to produce that same mix of products with virgin feedstocks. Thus, as shown by the dark cross-hatched Net Recycling Impact bar in Fig. 1, recycling saves over 13 million Btus per Mg recycled. As also shown in Fig. 1, upstream energy savings from recycling are an order of magnitude larger than the estimated 0.9 million Btus needed to collect, process and ship to market the recyclables collected in SLO County's curbside/on-site recycling programs.

Estimated energy generated from landfill gas (LFG) collected at the Cold Canyon landfill is also shown in Fig. 1 as a negative offset to the estimated energy required to collect and landfill refuse. As indicated in Fig. 1, the energy offset from LFG, estimated at 1.9 million Btus per Mg of collected refuse, is greater than the estimated total energy of about a million Btus required for collecting and landfilling refuse.

This portrayal of SLO County's refuse management system is based in part on the structural equations and assumptions in the DST that model how each Mg of refuse deposited in a landfill with a LFG collection system will anaerobically decompose over time, and how effectively the LFG collection system captures methane and other volatile gases released during that decomposition process. The defaults used in the DST, and thus in the calculations for Fig. 1, assume that landfill gases will be captured at greater than a 75% efficiency rate by the LFG collection system. Consequently, the DST estimates that each Mg of refuse landfilled at SLO County's Cold Canyon landfill yields a reduction in global energy demand of about a million Btus over the time period required for biodegradation of that refuse, as indicated by the Net garbage Impact bar in Fig. 1.

As previously discussed in Section 3 there is an ongoing substantive debate regarding capture efficiencies for LFG collection systems. But even without lowering the assumed capture rate down from 75%, recycling in SLO County is over thirteen times more effective at reducing global energy demand than landfilling. Thus, one would need to look at cost-effectiveness of recycling versus landfilling, recyclability of the materials remaining in refuse, or some other criterion besides energy efficiency to find a reason for not maximizing separation of recyclable materials from refuse so that they can be recovered for use in manufacturing recycled-content products.

3.2 Greenhouse gas reductions from recycling compared with landfilling

Fig. 3 shows estimated emissions of greenhouse gases in 2002 from collecting recyclables and refuse, and delivering those respective quantities to processing and landfill facilities. Fig. 3 also shows estimated greenhouse gas emissions during 2002 from operating the landfill, processing and shipping recyclables to end-use markets, and manufacturing processed recyclables into new products. Greenhouse gas emissions for these components of SLO County's recycling and disposal systems are shown as positive portions of the respective stacked bars for Recycling Impacts and Garbage Impacts in Fig. 3.

Greenhouse gas emission offsets from recycling, as a result of avoiding the manufacture of new products from virgin raw materials, is shown as the negative portion of the stacked bar for Recycling Impacts. Producing products such as newsprint, cardboard, glass containers, aluminum can sheet and plastic pellets with virgin materials emits 3,289 kilograms (kg) of carbon dioxide equivalents, compared with the 842 kgs emitted to manufacture this same quantity and mix of products with the recycled materials components that were, on average, in each metric ton of materials collected for recycling from SLO households and businesses during 2002. That is, using materials recycled in SLO County during 2002 to manufacture new products reduced greenhouse gas emissions to a level that is just 26% of the quantity of carbon dioxide equivalents that would have been emitted to make this same quantity and mix of new products from virgin raw materials.

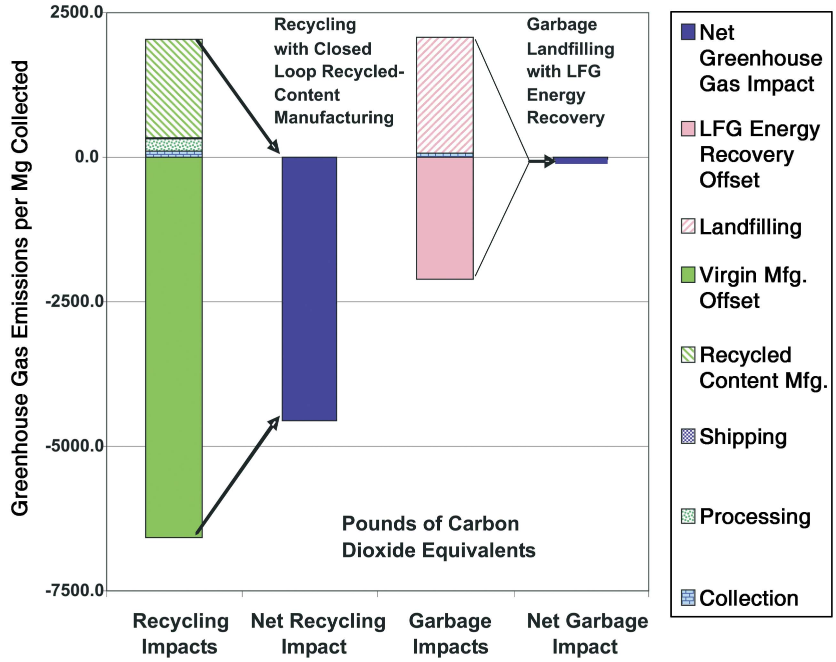

Fig. 3: Comparative greenhouse gas emissions for SLO recycling vs. landfilling

Estimated greenhouse gas offsets for energy generated from landfill gases collected at SLO's landfill in 2002 are shown as the negative portion of the Garbage Impacts stacked bar. These reductions in greenhouse gases that would otherwise have been generated at coal fired power plants to produce the energy generated by SLO's collected landfill gas were substantial enough, given the greater than 75% capture efficiency assumed for the landfill's gas collection system, to more than offset the greenhouse effect of methane emissions from gases that escape the landfill's gas collection system and carbon dioxide emissions from diesel fuels consumed in collecting refuse, hauling it to the landfill, and compacting it in place at the landfill.

The Net Garbage Impact bar in Figure 3 indicates that collecting landfill gases to generate energy reduces global greenhouse gas emissions by 11.7 kilograms of carbon dioxide equivalents per metric ton of collected refuse. Recycling, on the other hand, reduces greenhouse gas emissions by 2,268.8 kilograms for each metric ton of collected recyclables according to the Net Recycling Impact bar shown in Fig. 3. On this basis recycling is 194 times more effective per Mg of material handled than landfilling, even with energy generation from landfill gas, in terms of reducing global greenhouse gas emissions. Furthermore, the greenhouse gas impacts from collecting, processing and shipping recycled materials to market are more than an order of magnitude smaller than the upstream prevention of emissions achieved by using recycled rather than virgin materials to manufacture new products.

3.3 Acidification and eutrophication potential reductions from recycling compared with landfilling

As Fig. 3 did for greenhouse gases, **Fig. 4** shows the same advantages over landfilling, even with energy recovery from captured landfill gases, for collecting recyclables, processing them, and shipping them to end users where they can be used instead of virgin materials in manufacturing new products. **Fig. 5** shows a similar result for emissions of nutrifying substances. In these figures the potentials for environmental damages indexed on the bar graphs are, respectively, impacts from the release of acidifying and nutrifying compounds into the atmosphere and waterways.

As indicated in Figs. 4 and 5, recycling is five times more effective than landfilling at reducing emissions of acidifying substances that cause such environmental burdens as acid rain, and thirteen times more effective at reducing emissions of eutrophying substances that cause environmental damages such as nutrification of lakes and streams. Also, the environmental burdens for these two impact categories imposed by collection, processing and shipping recycled materials to end users are again quite small compared with the environmental burdens avoided when recycled materials replace virgin raw materials as input feedstocks for manufacturing new products.

3.4 Potential human health impacts from recycling compared with landfilling

The BEES environmental impact assessment methodology provides two indices for measuring threats to human health that SRMG used in assessing the public health burdens imposed by emissions of substances inventoried in the DST and its associated Database. These are (1) estimated disability-adjusted life year (DALY) losses caused by emissions of criteria air pollutants (nitrogen oxides, particulates, and sulfur oxides), and (2) an index denominated in grams of toluene equivalents for potential human health effects from emissions of toxic substances. DALYs "… account for years of life lost and years lived with disability, adjusted for the severity of the associated unfavorable health conditions".[9]

[9] (Lippiatt 2002), page 18

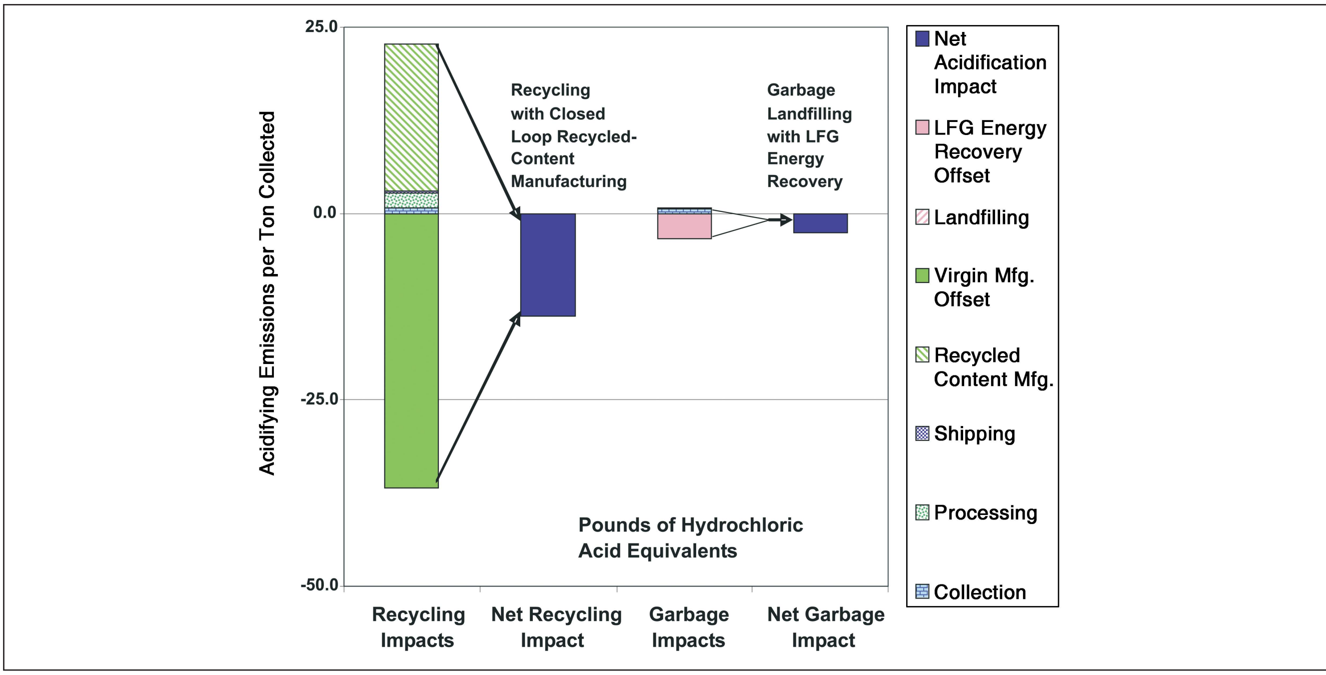

Fig. 4: Comparative acidification potential emissions for SLO recycling vs. landfilling

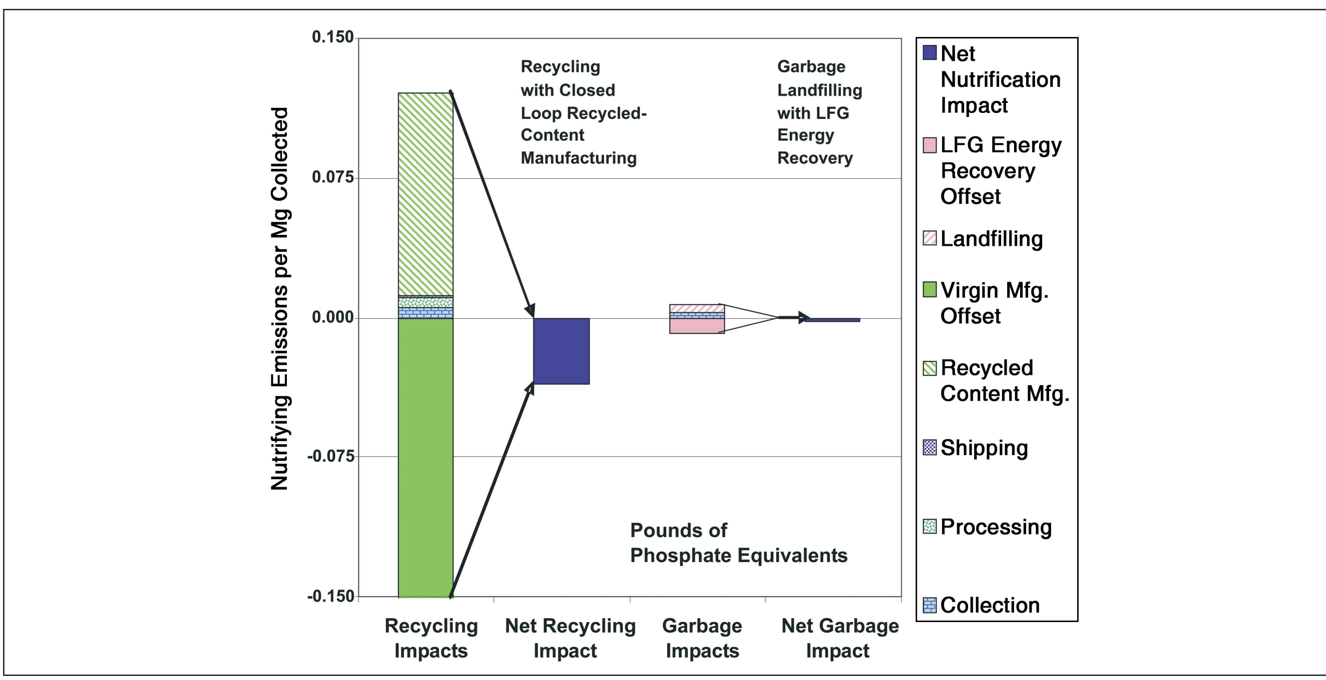

Fig. 5: Comparative eutrophication potential emissions for SLO recycling vs. landfilling

The DST provides emissions data for all three substances included in the DALY index, but only tracks emissions for sixteen of the more than two hundred toxic substances included in the BEES human health impact index for toxics. Nevertheless, the sixteen toxics that are tracked by the DST provide enough of an indication of the relative potential for human health impacts from toxic releases due to recycling and landfilling that their assessment via the BEES human toxicity index is reported here.

Fig. 6 shows estimated losses of microDALYs (a microDALY is one millionth of a DALY) in 2002 caused by criteria air pollutants emitted from collecting recyclables and refuse, and delivering those respective quantities to processing and landfill facilities. Fig. 6 also shows estimated microDALY losses during 2002 from operating the landfill, processing and shipping recyclables to end-use markets, and manufacturing processed recyclables into new products. These impacts on human health caused by air pollution are shown as positive portions of the respective stacked bars for Recycling Impacts and Garbage Impacts in Fig. 6. The offsets from avoidance of virgin-content manufacturing for recycling and avoidance of energy generation at coal-fired power

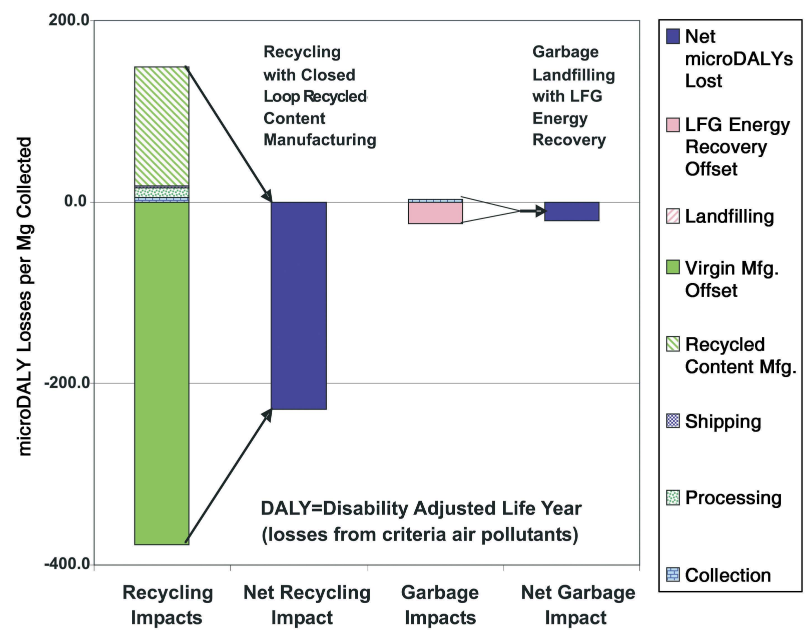

Fig. 6: Comparative DALY losses for SLO recycling vs. landfilling

plants for landfilling are shown as negative portions of the respective stacked bars to indicate their potential benefit in reducing DALY losses.

As indicated in Fig. 6 the virgin manufacturing offset (avoidance) benefits of recycling more than compensate for the microDALY losses caused by collecting, processing, and transporting recycled materials to end users, and by the processes employed by end users to manufacture new products from these recycled materials. In addition, the net reduction in microDALY losses per Mg of materials collected for recycling is more than ten times (an order of magnitude) larger than the net reduction in microDALY losses per Mg of waste materials collected for landfilling.

Fig.7 shows the potential for human toxicity impacts resulting from emissions of toxic substances during solid waste collection and handling operations. As with other environmental impacts from recycling operations, the potential for human toxic impacts is actually reduced by recycling because of the upstream offsets that accrue by avoiding the manufacture of new products using virgin raw material feedstocks. This is shown in

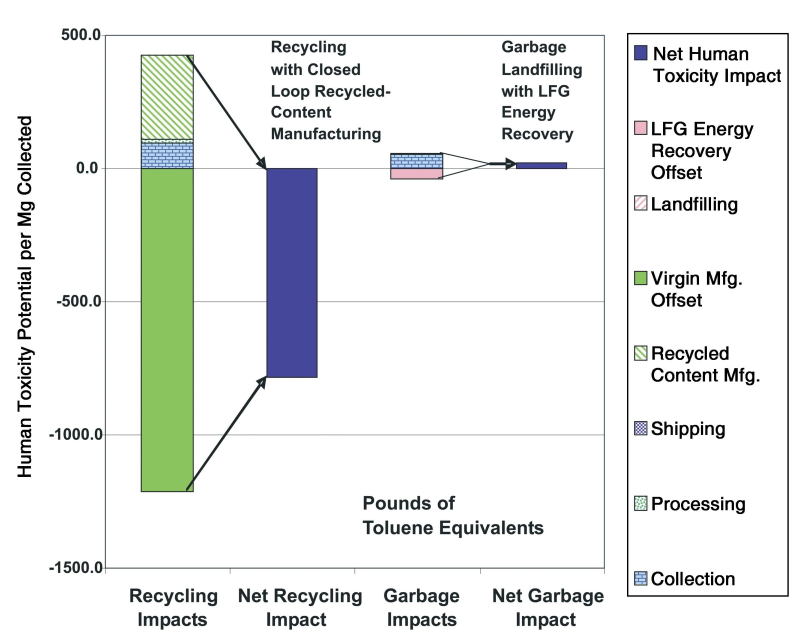

Fig. 7: Comparative potential human toxicity impacts for SLO recycling vs. landfilling

Fig. 7 by the negative portion of the stacked bar for Net Recycling Impact, indicating that recycling provides an environmental benefit by reducing emissions of toxic pollutants.

However, for the refuse collection and landfilling method of waste management there is a difference for human toxicity impacts compared with previously discussed impacts. That is, for emissions of compounds that are potentially toxic to humans the emissions offsets from landfill gas recovery and use for generating energy do not outweigh the environmental burdens caused by refuse collection and landfilling operations.

3.5 Potential ecological impacts from recycling compared with landfilling

The final impact measure evaluated by SRMG in the SLO IWMA study was for ecotoxicity. The BEES "ecological toxicity impact measures the potential of a chemical released into the environment to harm terrestrial and aquatic ecosystems…characterization factors for potential ecological toxicity use 2,4-dichlorophenoxy-ecetic acid (2,4-D) as the reference substance."[10] There are more than 150 substances in the BEES ecological toxicity assessment, but the DST and Database measure emissions for only fourteen of these. Nevertheless, as with the human toxicity potential measure discussed above, comparing ecotoxicity index scores for recycling and landfilling on the basis of those substances that are included in the DST still provides another important piece of information to use in evaluating the relative environmental burdens that may be imposed when managing solid wastes using these two methods.

Fig. 8 shows the ecotoxicity index values from emissions of these fourteen substances according to the BEES measure for assessing the potential for ecological toxicity from releases during collection and handling of solid waste materials. As was the case for every measure of environmental burden calculated in the SLO IWMA study, recycling reduces ecotoxicity potential. The reason is, as before, that avoiding production of goods from virgin materials reduces pollutant emissions more than the combined amount of releases from collection, processing, transporting, and manufacturing recycled materials into new products.

There is a new factor in this impact assessment, however, for refuse collection and landfilling. That is that recovery of energy from landfill gas actually increases ecotoxicity potential whereas it reduced environmental burdens for the other impact measures. What is not new is that recycling once again dominates landfilling with energy recovery due to the ecologically toxic pollutant releases that are avoided when products are made with recycled rather than virgin materials.

[10](Lippiatt 2002), page 22

4 Discussion of Results for the WA Ecology Study

The study that SRMG completed for Washington State's Department of Ecology focused on evaluating recycling against disposal just as the SLO IWMA study did. The WA Ecology study is discussed in this article along with the SLO IWMA study because the WA study compared residential curbside recycling against two disposal methods not used in SLO County – landfilling with LFG flaring and waste-to-energy (WTE) incineration. The WA study also reported results on a per household basis, which provides a perspective on the comparison of recycling against disposal in addition to results per Mg collected. Finally, the WA study gathered information on estimated economic costs of pollutant emissions. SRMG used these estimates to calculate estimated societal benefits from recycling to compare against net costs of recycling estimated for the four regions of WA.

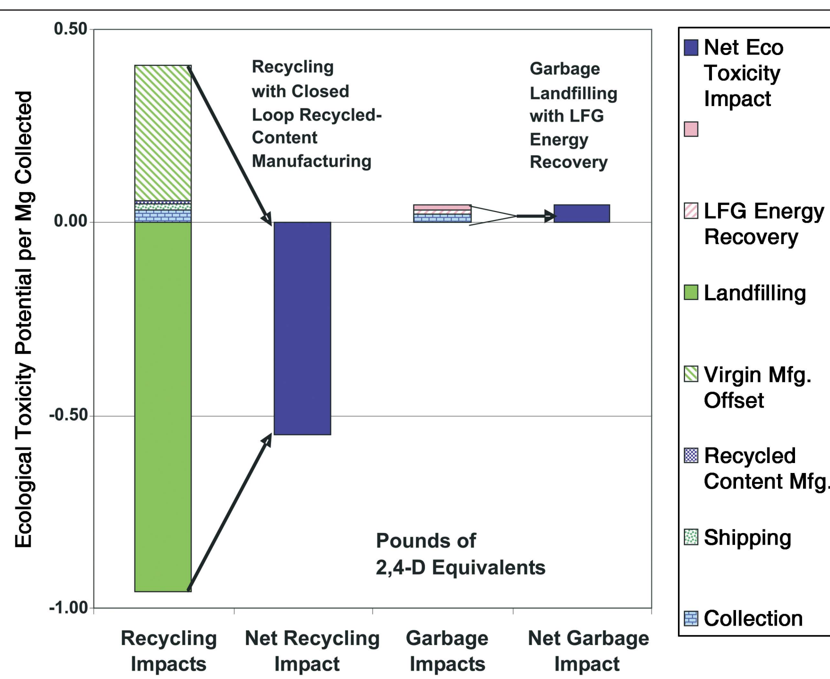

Fig. 8: Comparative potential ecological toxicity impacts for SLO recycling vs. landfilling

Table 1: Single-family residential curbside recycling costs and quantities in WA State in 1999

	Urban West	Urban East	Rural West	Rural East
Kg recycled per month	26	12	13	9
Curbside cost per month	$ 2.78	$ 1.86	$ 2.01	$ 1.66
Avoided disposal cost	$ 2.05	$ 1.01	$ 1.02	$ 0.31
Net curbside cost per month	$ 0.73	$ 0.85	$ 0.99	$ 1.35

Table 1 provides background information from the WA study. The table shows monthly costs per household for curbside recycling, including avoided disposal costs, and the average monthly amount recycled per household. The estimates of net cost include an offset for avoided disposal costs, but no offset for avoided garbage collection and transfer costs, even though reduced collection and transfer costs likely also occur when material is moved out of the garbage stream.

The types of materials collected from households for recycling in the four regions tend to be similar, except that at the time of the study the Urban East did not collect mixed paper and the Rural East did not collect glass. With these exceptions, the targeted materials included mixed paper, newspaper, cardboard, glass containers, tin-plated steel cans, aluminum cans, polyethylene terephthalate plastic bottles and high density polyethylene plastic bottles. Some jurisdictions within some regions also targeted other materials such as small scrap metal pieces and aseptic drink containers.

The disposal methods evaluated in this study were landfilling with LFG collection and flaring in all regions except the Urban East. Disposal in the Urban East was via WTE combustion, with delivery of electricity to the regional grid.

4.1 Energy savings per household for recycling versus disposal

Fig. 9 shows energy conserved by recycling materials rather then disposing of them in a landfill or WTE facility. The LCI calculations for recycling and disposal methods that underlay the bar graph shown in Fig. 1 are based on the same components and methodology detailed in the discussion regarding the SLO IWMA study, except that we did not include LCI data for the production of collection trucks as we did in the SLO study.

The presentation of results in Fig. 9, however, differs significantly from the presentation format used for the SLO results. First of all, Fig. 9, as well as the other figures shown below for the WA study, shows the net difference between recycling and the disposal method used in each region rather than showing the impacts for recycling and disposal separately. Second, net recycling versus disposal impacts are shown separately for the extraction/manufacturing and waste management portions of the life cycle of products[11]. Finally, reductions in energy use or in impacts from pollutant emissions are shown as positive numbers in figures portraying results for the WA study. Recall that figures portraying results for the SLO study showed virgin material and energy grid offsets as negative numbers.

What is similar for Fig. 9 on energy usage for curbside recycling in WA State regions with Fig. 1 on energy usage for curbside recycling in SLO County is that recycling saves energy relative to disposal because the upstream extraction/manufacturing energy savings (the upward pointing, lighter shade positive bars) from avoided virgin-content product manufacturing compared with recycled-content manufacturing are substantially larger than the additional energy (the downward pointing darker shade negative bars) used in the waste management system for recycling collection, processing and shipping to end-use markets.

[11]The use portion of the life cycle of products is not shown here because impacts from product use typically are the same whether the product is made from recycled or virgin content.

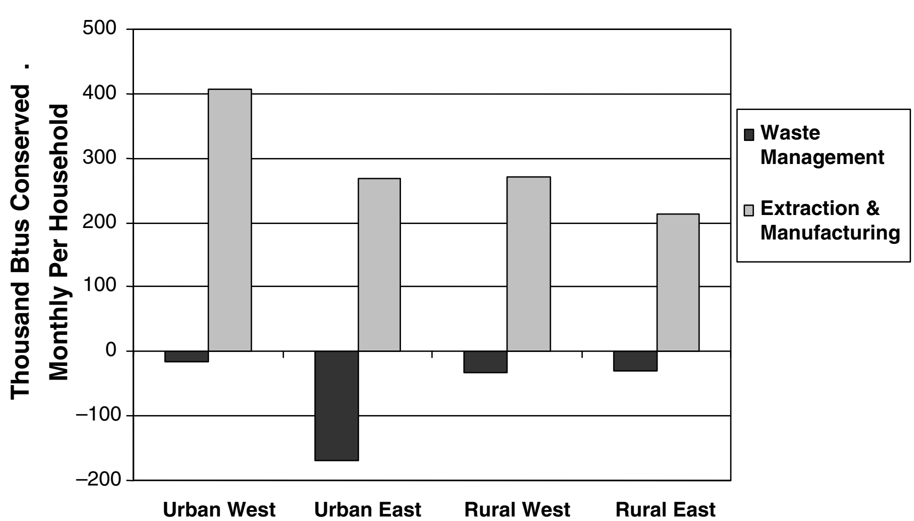

Fig. 9: Energy conserved by recycling

This conclusion holds in all four regions, even for the Urban East where WTE incineration provides a substantial electrical energy grid offset, as shown for the Urban East region in Fig. 9 by the longer dark bar for net waste management system energy usage due to recycling. The amount of energy that could be generated by incinerating materials that are currently recycled curbside each month in the Urban East would be about 138,000 Btus per household compared with energy conserved totaling about 269,000 Btus per household from using those recycled materials in place of virgin resources to manufacture products – a difference of almost 2 to 1.

4.2 Greenhouse gas reductions per household for recycling versus disposal

Fig. 10 shows the amount of greenhouse gas emissions prevented each month by curbside recycling in WA State's four regions. Here even the waste management systems for three of the regions show a reduction in greenhouse gas emissions for recycling. This is because, unlike SLO County, collected LFG is not used to generate energy but is simply flared. As a result the uncollected landfill methane has more global warming impact than the energy used to collect, process and market materials collected in each region's curbside recycling programs. Only in the Urban East does the recycling collection, processing and shipping system have a net negative impact on global warming because materials collected for recycling cannot be burned to generate energy – energy which otherwise would yield an offset to electricity generated by coal fired power plants for the regional energy grid. However, as indicated in Fig. 10, the upstream benefit from recycling outweighs this negative waste management system impact by about 4 to 1.

4.3 Acidification and eutrophication potential reductions per household for recycling versus disposal

Results in the WA study for the four regions on acidification and eutrophication potentials are similar to results shown above for energy and greenhouse gases. That is, recycling's upstream benefits dominate its downstream impacts compared with either landfilling or WTE combustion, so that recycling reduces acidification and eutrophication potentials for all four regions of WA.[12]

4.4 Human toxicity potential reductions per household for recycling versus disposal

One other comparison for recycling versus disposal that is worth including here is for human toxicity impacts. This is because evaluation of the potential impact of pollutant emissions on human health entails different pollutants indexed using relative weights that are also quite distinct from the weights and pollutants used to index potential global warming, acidification and eutrophication impacts. Thus, it is interesting to show how recycling rates relative to landfilling with LFG flaring and to WTE incineration for this impact category.

Fig. 11 shows (in the same format as the two previous graphs) the impacts of recycling versus disposal on human toxicity potential in the four regions for the extraction/manufacturing and waste management phases of the life cycles for materials recycled curbside in each region. As indicated in Fig. 11, recycling again outperforms disposal for this impact category. In fact, recycling is preferable to landfill with LFG flaring by substantial margins in each of the three regions using this disposal method, and is also preferable by only a slightly diminished margin to disposal via WTE incineration in the Urban East.

4.5 Economic valuation of recycling's non-market societal benefits in comparison to Its market costs

Table 2 shows the net monthly cost per household for curbside recycling and estimated societal values for the global warming, acidifying and eutrophying pollutant emissions

[12]The interested reader can review the actual results for these two impacts in (Morris 2002).

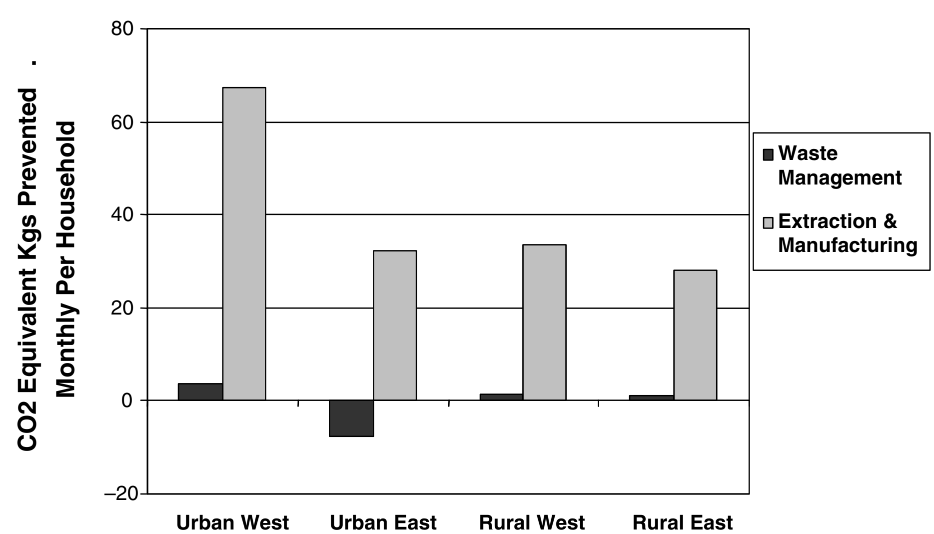

Fig. 10: Greenhouse gas emissions prevented by recycling

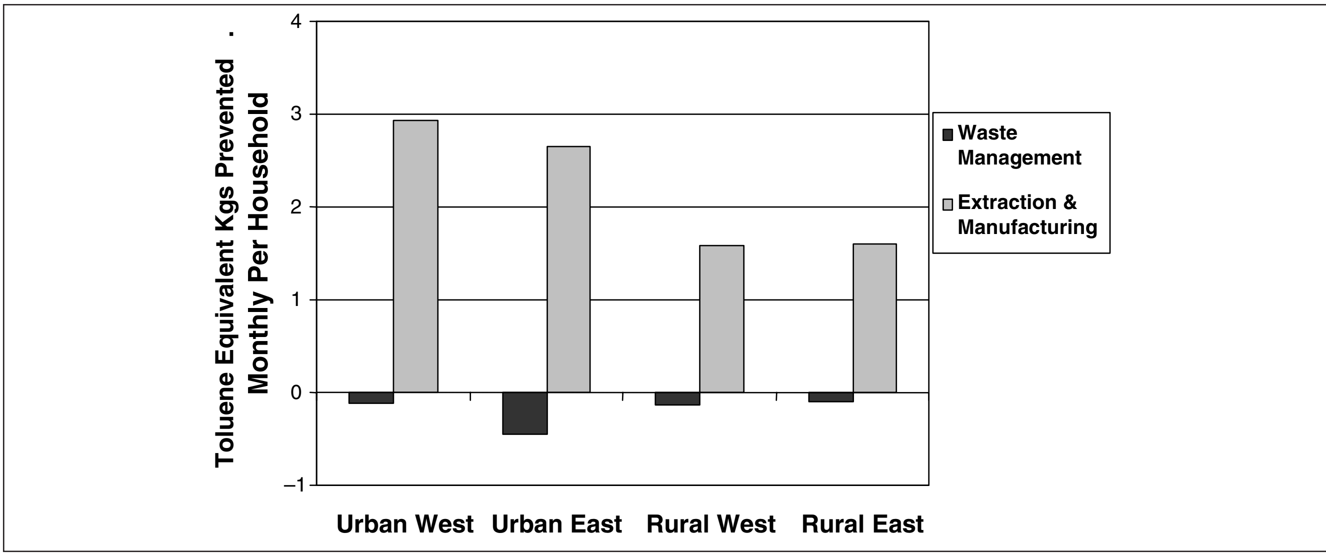

Fig. 11: Human toxicity emissions prevented by recycling

reductions yielded by curbside recycling in each region of WA State. The valuations for reductions in global warming, acidification and eutrophication potentials shown in Table 2 are based on midranges for pollutant costs surveyed in (Ecology 2002) and the BEES index weights for pollutants in each of the three impact categories.

As indicated in Table 2, estimated societal benefits from reductions in global warming, acidification and eutrophication potentials as a result of curbside recycling more than offset recycling's net cost in the high-recycling Urban West. Estimated societal benefits come close to outweighing net costs in the Urban East and Rural West, but only offset about 65% of average net cost for Rural East curbside recycling programs.

The results discussed for SLO County on the quantitative benefits of recycling for human health and ecological toxicity indicate that recycling reduces environmental burdens imposed by waste management activities for impact categories in addition to global warming, acidification and eutrophication. Thus, although much more work needs to be done to develop reliable estimates for the societal value of pollutant emissions reductions, the data shown in Table 2 suggest that recycling is a waste management activity whose societal costs are adequately justified by the non-market benefits that result from recycling reducing society's environmental and public health burdens from pollution.

5 Conclusion

Results from the two studies described in this article show that recycling has substantial benefits compared with disposal in terms of reducing energy consumption and environmental burdens imposed by methods used for managing solid wastes. Specifically, recycling compared with disposal reduces potential impacts of solid waste management activities on all public health and environmental impact categories examined – global warming, acidification, eutrophication, human health effects from criteria air pollutants, human toxicity, and ecological toxicity. This conclusion holds regardless of whether disposal is via landfill without LFG collection, landfill with LFG collection and flaring, landfill with LFG collection and energy recovery, incineration without energy recovery, or WTE incineration. For several environmental impact categories the net environmental benefits of recycling are reduced by WTE incineration as compared with landfilling, but the conclusion remains the same – recycling is environmentally preferable to disposal by a substantial margin.

The main reason for this conclusion is that the pollution prevention and resource conservation benefits of manufacturing products out of recycled materials rather than virgin raw materials tend to be an order of magnitude larger than the environmental burdens imposed by recycling collection,

Table 2: Recycling net costs compared with societal value for three environmental impact benefits

Monthly per household	Urban West	Urban East	Rural West	Rural East
Kg recycled	**26**	**12**	**13**	**9**
Net curbside cost	**$0.73**	**$0.85**	**$0.99**	**$1.35**
Global warming prevention benefit	$0.94	$0.33	$0.46	$0.39
Acidification prevention benefit	$0.97	$0.33	$0.44	$0.42
Eutrophication prevention benefit	$0.23	$0.06	$0.05	$0.06
Total pollution prevention benefit	**$2.14**	**$0.72**	**$0.95**	**$0.87**

processing and shipping systems. These upstream benefits of recycling also are much larger than the energy production offsets from whatever method is used to generate energy directly from waste. Thus, recycling newspaper, cardboard, mixed paper, glass bottles and jars, aluminum cans, tin-plated steel cans, plastic bottles, and other conventionally recoverable materials found in household and business municipal solid wastes consumes less energy and imposes lower environmental burdens than disposal of solid waste materials via landfilling or incineration, even after accounting for energy that may be recovered from waste materials at either type disposal facility.

Estimates of the economic value for recycling's pollution prevention and resource conservation benefits suggest that the societal value of these benefits outweighs the additional economic cost that is often incurred for waste management when systems for handling solid wastes add recycling trucks and processing facilities to their existing fleet of garbage collection vehicles and existing transfer and disposal facilities. This may be small recompense for the local waste management agency that is hard-pressed for cash to pay its waste management costs, especially in jurisdictions that have neither convenient methods for imposing quantity-based fees on waste generators – with those fees structured to cover the costs of recycling as well as garbage management programs – nor political support for doing the right thing environmentally.

However, ongoing developments in the trading of credits for emissions reductions, such as already exists for sulfur dioxide emissions through EPA's emissions permits trading program developed under the Clean Air Act and is under consideration through various experiments for greenhouse gases and other pollutants, do offer hope for the future. For example, a greenhouse gas credit of just $9 a ton would by itself offset the net costs of the average recycling program in the Urban West region of Washington State. Voluntary greenhouse gas emissions reduction agreements already yield trading at a price of about $1, and predictions of more than $10 per ton for CO_2 emissions credits under compulsory agreements are typical[13]. Whether these might accrue to recycling programs through direct payments for emissions reductions yielded by their recycling quantities, or through higher prices for recycled materials as a result of emissions credits paid to manufacturers of recycled-content products, the net result will be to better compensate communities for the societal value of their recycling programs. In addition, focus within private industries on pollution prevention, whether voluntary or compulsory, in the long run will also favor recycled-content manufacturing and tend to drive prices for recycled materials up.

[13]See, for example, (Edmonds 1999) for one study that predicts carbon emissions trading levels of $50 per metric ton of carbon equivalents on worldwide carbon emissions trading markets. This is equivalent to a trading price of over $12 per ton of CO_2.

In terms of direction for additional research, this article highlights the need for better estimates of societal value for avoided environmental burdens. In addition, there is an evident need for life cycle emissions data on additional pollutants besides the handful of pollutants used for the life cycle analyses in the two studies discussed herein. There is also need for life cycle research on other materials that end up in solid waste streams, from used electronics and tires to organics such as yard debris, food scraps and soiled paper. This research is necessary to illuminate the extent to which environmental burdens can be avoided by diverting these additional materials from disposal systems into physical recovery systems that recycle them into available beneficial uses – for example, into manufacturing feedstocks for production of new goods in the case of consumer durables and, in the case of organic materials, into compost process feedstocks for eventual applications in agricultural and home gardening.

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